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Swarm Robotic Network Using Lévy Flight in Target Detection Problem

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Abstract: One approach in swarm robotics is homogeneous system which is embedded with sensing, computing, mobile and communication components. In this study, a target detection problem, which is one of navigation problems, was employed. Once a robot detects a target, robots immediately communicate with a base station via intermediate relay robots due to the multi-hop transmission of wireless communication. Therefore, this control task is completed with connectivity of the network. In a target detection problem, we must improve the performance of exploration as well as connectivity of the network. This study investigates the performances of the two kinds of random walk algorithm in navigation while loosely ensuring connectivity of the robotic network based on our previous study.

Keywords: Swarm Robotics, Lévy Flight, Wireless Sensor Networks, Target Detection Problem

1. INTRODUCTION

Swarm Robotics (SR) [1][2] have attracted much research interest in recent years. Generally, the tasks in SR are difficult or inefficient for a single robot to cope with. Thus, SR and multi-robot systems overlap each other. Sahin [3] enumerated several criteria[1] for distinguishing swarm robotics as follows:

- autonomy: Each robot should be physically embodied and situated.
- redundancy: Group sizes accepted as swarms is 10 to 20.
- scalability: SR system should be able to operate under a wide range of group sizes.
- simplicity: Each robot should employ cheap design, that is, the structure of a robot would be simple and the cost for it would be cheap.
- homogeneity: SR system should be composed of homogeneous individuals. This enhances the above 2nd and 3rd criterion.

Following the last criterion, homogeneous controllers for individuals are desirable for SR systems. Additionally, this approach does not assume the existence of an explicit leader in swarm robots due to the above criteria. This results in that a collective behavior emerges from the local interactions among robots and between the robots and the environment. Therefore, SR systems are required for that individuals show various behaviors through interactions although the individuals are homogeneous.

The typical control tasks in SR are navigation, aggregation, formation and transport requiring distributed collective strategies [2]. In this paper, we copes with a target detection problem, which is one of navigation problems. In this control task, several robots can communicate with each other via wireless sensor networks (WSN)[4][5] due to the multi-hop transmission to achieve collective exploration. As soon as a robot detects a target, the information is sent from the robot to the base station via intermediate relay robots. Therefore, all robots should be “connected” to the base station via WSN.

Our research group investigated communication range and the number of robots required for a SR network to achieve connectivity based on percolation theory[6-8] in computer simulation [9]. According to the results obtained in [9], we conduct a series of real experiments in this work. Also, we must consider the performance of exploration as well as connectivity of the SR network in a target detection problem. Therefore, we improve exploration strategies to enhance the performance.

In this paper, we employ a Brownian random walk, which employs the constant step size, and Lévy flight[10], which employs the step size following Lévy probability distribution, in order to investigate the effect of the step size of the random walk and the number of robots in a target detection problem. Addition to this, the swarm robotic behavior emerged from each random walk are analyzed.

As a related work, Sutantyo *et al.* [11] studied the effect of Lévy flight on a target detection problem by real underwater swarm robots. Their experimental environment is an aquarium with size 2.5 m $\times$ 2.5 m $\times$ 1.5 m. Their control task is to aggregate around targets after a robot detects a target and attracts other robots. They employed the firefly optimization algorithm with Lévy flight to generate the “attractive” and “random” behavior of the robots. They employed the blue-light intensity as communication. Thus, they neither used explicit verbal communication nor ensured the connectivity between the robots. Moreover, they did not assume communication with the outside of the swarm robots after detecting a target. The control task of them is different from the one of our study and their environment is much smaller than ours described later.

The paper is organized as follows. The next section shows the structure of the mobile robots. Section 3 explains two random walks. Section 4 describes the controller of the robots and how to implement random walk and Lévy flight in the controller, respectively. Section 5 shows the setting and results in real experiments. Section 6 discusses the results. Conclusions are given in the last

† Yoshiaki Katada is the presenter of this paper.
[1]Sahin [3] claimed that these criteria should be used as a measure of the degree of SR in a particular study.

section.

2. SETUP FOR SWARM MOBILE ROBOTS

Differential wheeled robots (Fig. 1) were used in this experiment. The robot's diameter and height are approximately 170 mm and 75 mm, respectively. The robot is equipped with four infrared distance sensors located at its front for measuring the distance to other robots and walls, and two infrared sensors located at both ends of the body for detecting a target. The maximum detection ranges of the former infrared sensor and the latter infrared sensor are 300 mm and 200 mm, respectively. The robot's processor is the Arduino microcontroller, which gets sensory inputs and outputs signals to control two wheels through motor drivers. The robot is equipped with wireless devices, XBee. XBees, based on ZigBee wireless standard, can compose wireless ad hoc networks, where nodes can communicate with each other via multi-hop path. A XBee equipped with each robot is set as a router of the network. As a target, an infrared-emitting ball is employed to make handling easy, which is the official ball for RoboCup Junior [12]. Its infrared rays are distinguishable from those emitted by the distance sensor described above due to the different wavelength.

3. RANDOM WALKS

In this study, we cope with a navigation task. We assume that robots have no prior knowledge of the environment. In these scenarios, random walks are general exploration strategies. A random walk with a constant step size is well known. On the other hand, Lévy flight is a random walk whose step size varies according to a Lévy probability distribution [10]. It is reported in [13] that Lévy flight is useful for the environment where targets are distributed sparsely and randomly.

Lévy probability distribution for a step size can be approximated in the following [14]:

$$p(d) \simeq \gamma d^{-\alpha} \tag{1}$$

where d is a step size, γ is the scaling factor and α is a parameter varying the shape of the probability distribution. In this study, we set γ to 1.0 and α to 1.2 according to the recommendation in [13]. Fig. 2 shows Eq. (1) with $\gamma = 1.0$ and $\alpha = 1.2$ over the step size range $1 \leq d \leq 30$.

4. CONTROLLER

4.1. Design methods in SR

Controllers in SR are required to enhance the criteria described in Sec. 1. Thus, the methods to design such controllers can be classified into two categories: behavior-based design and automatic design [2]. The both methods are based on the interaction between robots and environment. The former develops controllers by hand and the latter does by soft computing. Reinforcement learning (RL) and evolutionary robotics (ER) are representative of automatic design. Currently, RL and ER are useful in simulated environment. However, it is difficult to ensure consistent behavior of robots in real environment with the one obtained in simulated environment [15-19]. Therefore, most researchers aiming at real robots in SR employ the behavior-based design.

Subsumption architecture (SSA) proposed by Brooks[20] is a representative of behavior-based design. In behavior-based design for SR, individual behavior of swarm robots is adjusted iteratively based on the interaction among the robots and between the robots and environment [2]. As a format to describe such individual behavior, finite state machines are often used. On the other hand, augmented finite state machine is used to describe modules in a control layer for SSA explained in the next subsection. According to these, we employ SSA as a format to describe behavior of individuals which compose swarm robotic network.

4.2. Layer Structure of SSA

Fig. 3 shows a layer structure of SSA implemented in this swarm robots. The SSA to achieve the control task in this study is composed of the following three layers: *transmission*, *obstacle avoidance* and *target exploration*. A capital I in Fig. 3 indicates *inhibition* by which a lower layer is inhibited when an upper layer is activated [20]. Each layer is composed of some modules connected to each other.

Behavior of each layer can be explained as the following; In the target exploration layer, the *explore* module

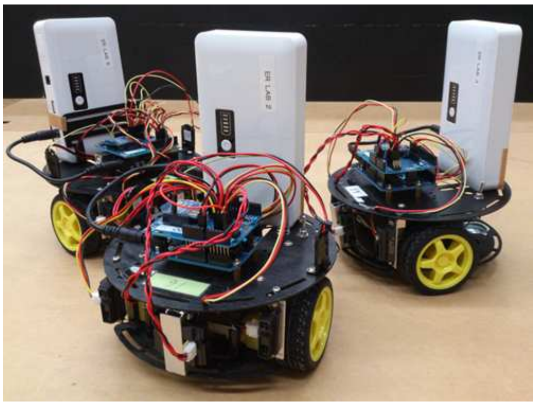

Fig. 1 Setup for swarm mobile robots

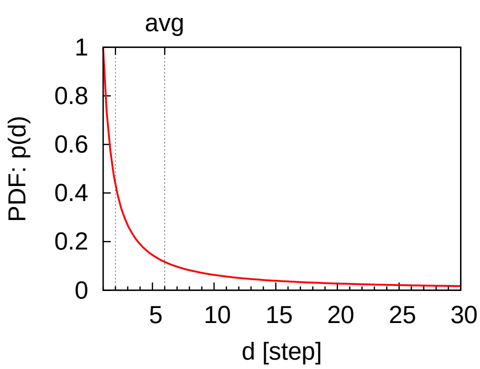

Fig. 2 Lévy probability distribution

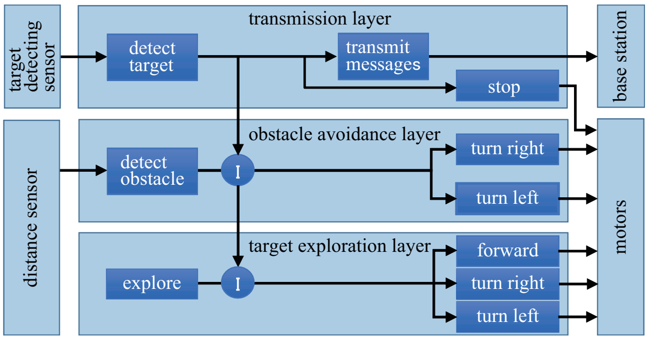

Fig. 3 Layer structure of SSA

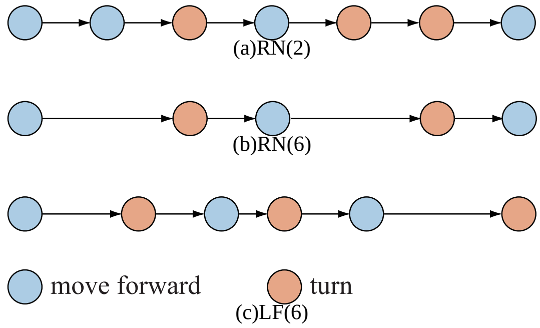

Fig. 4 Transition between move-forward phase and rotate phase in navigation

sends messages to one of the following three modules: *forward*, *turn right* and *turn left*, where *forward* means moving forward and *turn right* (*left*) rotating clockwise (counter clockwise) at the position. In the obstacle avoidance layer, the *detect obstacle* module sends messages to either *turn right* or *turn left* according to the sensory inputs from distance sensors described in Sec. 2, in order to avoid the obstacles which the robot faces. In the transmission layer, the *detect target* module sends messages to the *transmit messages* module and the *stop* module when the sensory inputs from the infrared sensors for detecting a target are beyond a threshold. The *transmit messages* module transmits messages to the base station via intermediate relay robots. The *stop* module sends messages to its own motors to stop them.

4.3. Implementation of exploration strategies

In the reminder of this paper, a random walk with a constant step size is simply called "random walk" to distinguish from Lévy flight. These strategies are implemented in the target exploration layer. The details are described in the following subsections.

4.3.1. Random Walk

For random walk, the direction of a move for each step is determined at random while the step size of a move is constant. For the differential wheeled robots used in this study, it is difficult to move forward with a constant step size and to rotate in the predetermined direction simultaneously. Therefore, the whole steps are divided into the move-forward phase and the rotation phase (Fig. 4). In the move-forward phase, a robot moves forward driving two wheels (corresponding to the *forward* module in Fig. 3). One step in the move-forward phase is set to 6 seconds according to the results in the preliminary experiment. In the rotation phase, a robot determines the direction of rotation and selects an angle of rotation randomly from $\{45, 90, 135\}$ degree. Then, a robot rotates until the selected angle is achieved (the *turn right* or *turn left* module in Fig. 3). In the reminder of this paper, we write RN(*) as an abbreviation of random walk, where "*" in parentheses indicates the average step size.

The move-forward phase and the rotation phase are implemented as follows; In RN(2), a step size is set to 1 in the move-forward phase and the phase to be executed is selected randomly at each step (Fig. 4(a)). Thus, the transition from the move-forward phase to the move-forward phase is possible. In this case, the average step size is effectively 2. In RN(6), a step size is set to 6 in the move-forward phase and the transition between the two phases occurs at 100% in order to compare the performance of Lévy flight.

4.3.2. Lévy Flight

Lévy flight employs the move-forward phase and the rotation phase as random walk does. A step size in the move-forward phase is determined according to a Lévy probability distribution described in Sec. 3. The transition between the two phases occurs at 100%. In this study, the maximum step size is set to 30 based on the results in the preliminary experiment. Thus, the average step size is effectively 6. We write LF(6) as an abbreviation of Lévy flight in the reminder of this paper.

5. EXPERIMENT

5.1. Experimental Environment

We conducted a series of real experiments in the corridor on the 6th floor in the 1st building in Neyagawa campus of Setsunan University (the yellow part in Fig. 5). There are some class rooms adjacent to this corridor. Thus, the environment is surrounded by walls[2]. A target (an infrared-emitting ball described in Sec. 2) was placed at the lower left corner in Fig. 5. At the upper right corner, a wireless base station was placed. The base station is a laptop with the same XBee as those equipped with swarm robots. The XBee equipped with the base station is set as a coordinator. At the beginning of each trial, swarm robots were always placed at the same initial position, the lower right corner, next to the base station at random orientations (Fig 5). In this environment, the base station and the robot located near the target can not be in line-of-sight communication because the distance between the base station and the target is longer than the communication range of the XBee.

[2] We assume that the doors of the rooms are closed during the experiment.

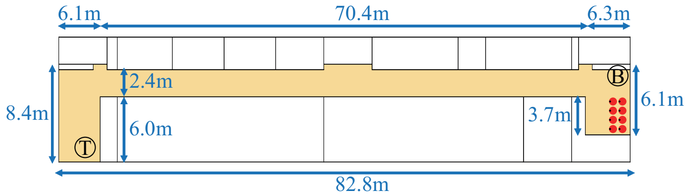

Fig. 5 Experimental setup for target detection problem (B: base station, T: target)

5.2. Setting of Real Experiments

In this control task, swarm robots explore the environment, detect a target located so far (around 80 m) from the base station as not in line-of-sight communication and send a message to the base station via intermediate relay robots. Therefore, all robots should be "connected" to the base station via swarm robotic network mentioned in Sec. 1. It was found in the preliminary experiment that the XBee in the environment can communicate with other XBee longer than the indoor communication range calculated by the specifications. It is around 54 m. Thus, the distance of the communication range relative to the longer direction of the environment is $54/82.8 \simeq 0.65$. This results in that the number of robots required for a SR network to achieve connectivity in a square space is from 20 to 34 following to the recommendation in [9]. However, connectivity in the rectangular space would be achieved by a smaller number of robots because a square space is assumed in the reference[9]. Thus, we conducted a series of real experiments varying the number of robots $N \in \{10, 15, 20\}$. One trial ends either when the base station receives the message from the robot detecting a target [3] or when 1800 sec (30 min.) are performed without receiving the message. As a controller of the swarm robot, the SSAs described in Sec 4 were employed varying the exploration strategy in the target exploration layer: random walk (RN(2), RN(6)) and Lévy flight (LF(6)). We conducted 10 independent runs for each experiment.

5.3. Experimental Results

Table 1 shows the time for detecting the target for each exploration strategy varying the number of robots. In the table, "—" indicates the trial where the task was not achieved and "average" indicates the average time of each successful trial. Additionally, Fig. 6 shows the success rate for each exploration strategy. The success rate is higher in the order of RN(2), RN(6) and LF(6) except for RN(2) with $N = 10$. Here, the success rate of LF(6) is especially high. Moreover, the time to detect the target for LF(6) is shorter than those for RN(2) and RN(6) in almost all the trials for the same N. For LF(6), we confirmed that the times are not significantly different for Ns. When one trial ends, the base station sends a message to stop all the robots. At that time, we confirmed that all the robots stopped each trial even though there were small time delays. From these results, we can say that connectivity was achieved when or not when the task was completed.

[3] In the reminder of this paper, the robot's detecting a target is synonymous with that the base station receives the message from the robot.

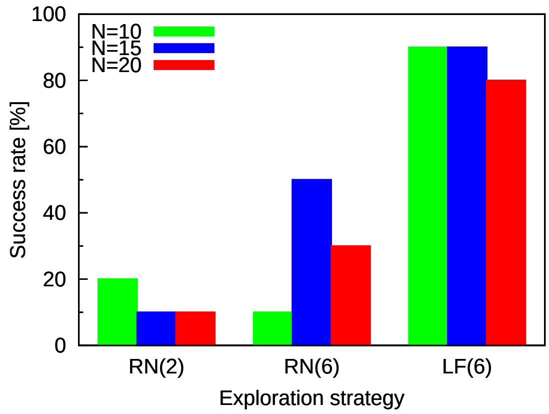

Fig. 6 Success rate for each exploration strategy

6. DISCUSSION

In the previous section, we confirmed that the success rate of LF(6) was extremely high. In this section, we investigate those results from the view point of features of Lévy flight described in Sec. 3.

Fig. 7 is a sketch map of the environment divided into four areas (further from the base station in the order of A, B, C and D). For each area, we calculated the average number of robots in all the runs just when one trial ended. These results are shown in Fig. 8. For RN(2), nearly 40 percent of the robots stayed in Area A (blue) and only about 10 percent of the robots reached Area C (gray) and D (red) (Fig. 8(a)). Thus, it was difficult for the robots to get out of the vicinity of the initial positions and go far away from there. Actually, there is an elevator hall in Area A and the boundary between Area A and B forms a bottleneck. For RN(6) and LF(6), from 20 to 40 percent of the robots reached Area C and D (Figs. 8(b) and 8(c)). Considering the low success rate of RN(2), a large step size is favorable to get out of Area A and B.

The following is a comparison between RN(6) and LF(6). In RN(6), from 10 to 20 percent of the robots stayed in Area A while in LF(6), from 30 to 40 percent of the robots stayed in Area A. However, we have confirmed the connectivity in Sec. 5.3. In Fig. 8, we can not find the reason why LF(6) outperformed RN(6).

Next, we observed the behavior of the robots with RN(6). Although less than 10 percent of the robots reached Area D, it took a lot of time to reach there. What was worse, robots passed by the target without detecting it due to the relatively large constant step size even though they reached the vicinity of the target. For LF(6), it took less time to reach Area D than for RN(6) and robots detected a target in the vicinity of it due to the small forward movements and the turns following them. This would be the reason why LF(6) outperformed RN(6).

Table 1 Time for detecting the target

algorithm	RN(2)			RN(6)			LF(6)		
number of robots	10	15	20	10	15	20	10	15	20
trial 1	—	—	—	—	1446	928	1585	650	931
trial 2	—	1328	—	—	—	1336	1666	634	1140
trial 3	1537	—	—	—	—	—	—	—	—
trial 4	—	—	—	—	—	—	1405	1328	1017
trial 5	—	—	—	—	—	—	891	1634	949
trial 6	—	—	—	—	1558	—	1031	1083	1167
trial 7	—	—	—	1594	1536	—	1248	1072	1428
trial 8	—	—	—	—	—	—	1135	1279	—
trial 9	1676	—	—	—	1537	—	1148	1392	1117
trial 10	—	—	1690	—	1708	1352	950	815	997
average [s]	1606	1328	1690	1594	1557	1205	1229	1099	1093

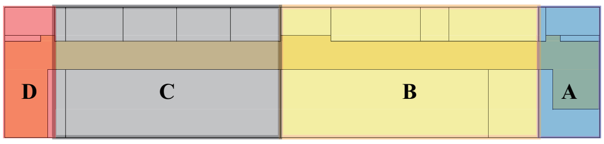

Fig. 7 Environment divided into four areas

7. CONCLUSIONS

In this paper, we conducted a series of real experiments on a target detection problem by swarm robotic network in order to investigate the effect of the step size of the random walk and the number of robots. We confirmed that the variable step size according to a Lévy probability distribution, that is, Lévy flight is useful for an exploration strategy in the target detection problem. Additionally, for Lévy flight the times detecting the target are not significantly different for the number of robots ensuring the connectivity of the robotic network. In this experimental environment, a prerequisite for achieving the task was getting out of the vicinity of the initial positions while a few robots stayed there to ensure the connectivity of the robotic network at the end of the trial. This seems like foraging behavior of insects in which the elevator hall around the initial positions is a nest and the target is food. In this experimental setup, we do not assume the existence of explicit mechanism to maintain the connectivity of the network, that is, the cooperation among the robots. However, such behaviors were emerged from the interaction between the environment surrounded by the walls and enough number of robots.

In future works, we will add the functions to estimate a position of the target after detecting the target and to make swarm robots home to the base station. Addition to this, we will expand our approach to the open space, that is, environment unsurrounded by walls or outdoor.

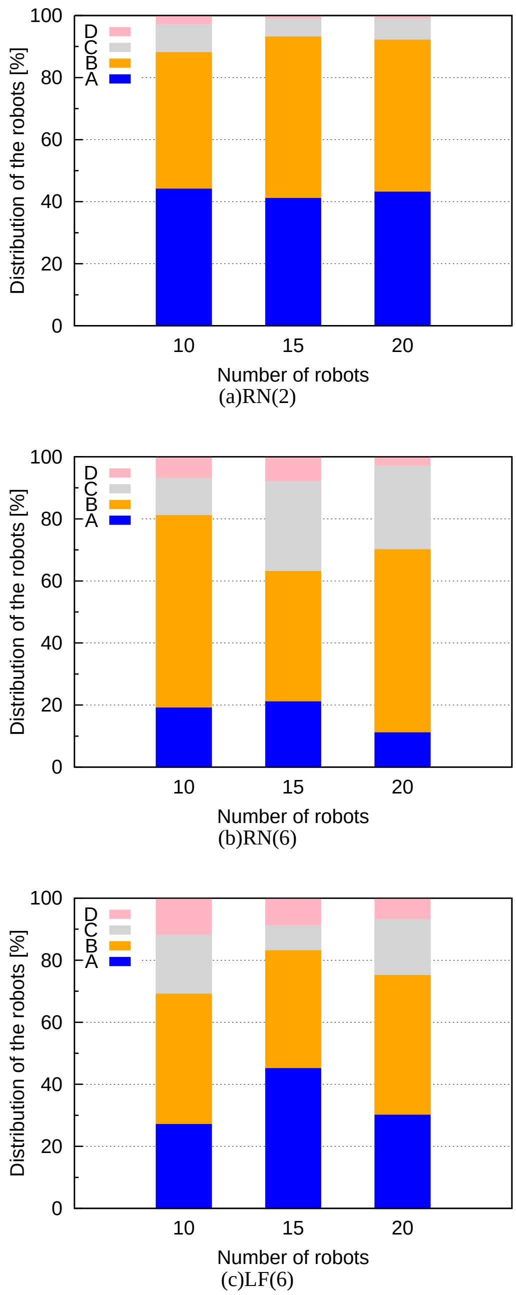

Fig. 8 Distribution of the robots in each region for the number of robots

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